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SPH for design of an industrial scale composites recycling process

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Abstract—Composite waste poses a significant problem in many industries today. There are both environmental and financial motivations for finding alternatives to disposing of the waste in landfills. Recycling the composite materials offers one such alternative. Typically, this involves removing the matrix and cutting the fibres into short, discontinuous lengths. A key requirement in producing commercially valuable composites from these discontinuous fibres is a high level of fibre alignment. A technology, invented at the University of Bristol called High Performance Discontinuous Fibre (HiPerDiF), produces such material [1]. The next stages for this technology involve upscaling the design from its current laboratory scale to an industrial-scale machine. This requires a higher throughput of fibres whilst maintaining the high level of alignment. The alignment mechanism is driven by fluid dynamics and is modelled using SPH in this work. The short fibres are suspended in a water jet and sprayed between thinly-spaced parallel plates. This work aims to validate the SPH model using experimental results and conduct an initial investigation into some design parameters that could influence alignment. It is shown that the model captures the trend of the fibre alignment well and that plate spacing has a much larger effect on alignment than jet velocity.

I. INTRODUCTION

Over the recent decades there has been a large increase in the manufacture rate of composite materials for the production of high quality parts. They are favoured over metal components largely due to their lower resulting weight. This is especially true in industries where it is important for components to be lightweight, such as the aerospace industry. As the need for a reduction in emissions increases, in order to try and delay global warming, other industries, such as the automotive industry are also looking towards composite materials for weight saving. This increased production in composites has led to a need to find ways of recycling composite components once they get to the end of their useful life. Until now, most composite products are simply disposed of in landfill, however, governments are introducing directives and legislation in an attempt to reduce the amount of composite waste being produced [2]. This means that it is now more important than ever to find alternatives. The obvious alternative is to recycle the composite material. This is typically done by removing the composite polymer matrix and cutting the fibres

(e.g. carbon fibres) into short lengths [3], then the short fibres must be remanufactured into a useful product.

Whilst the focus of this work is the recycling of composites, any method manufacturing short fibres is not limited to those that have been recycled. Indeed, short fibre composites can have benefits over those of continuous fibre composites. These benefits include a reduction in manufacturing defects that arise as a result of manipulations [4], an increase in the ease of production of components with more complex geometries as short fibres have better formability and also the ability to produce materials that have pseudo-ductile response under loading as the fibres can deform and slip at the discontinuities [5]. However, the benefits of discontinuous fibre composites can only be realised if they retain the same high strength/weight and modulus/weight ratios as continuous fibre composites. This can be achieved by producing materials with a high level of alignment of the fibres. One method proposed to achieve the manufacture of these highly-aligned discontinuous fibre composites is the High Performance Discontinuous Fibre (HiPerDiF) method [1]. The HiPerDiF method, which is described in greater detail in the next section, produces discontinuous fibre composites with excellent mechanical properties from recycled (reclaimed) continuous fibre structures. The high level of alignment of the fibres is mainly achieved through a momentum change induced by the short fibres, which are suspended in a water jet and sprayed through a nozzle, hitting a set of parallel plates.

The next step for the HiPerDiF technology is to increase the production rate. This will primarily involve increasing the throughput, however it must be ensured that the level of alignment is maintained. The aim of this work is to develop and validate an SPH model of the HiPerDiF alignment mechanism in order to investigate the fluid mechanics behind the process and thus inform the upscaled design.

The motivation for choosing SPH to model this problem is due to its excellent ability to model free-surface flows. This problem is also one of a strongly coupled fluid-structure interaction. In this work, the fibre is treated as a rigid body. Treating solids in this way as part of an SPH simulation has

been done by several authors in the literature such as Hashemi *et al.* [6] who used a 2D WCSPH method to simulate flow around circular bodies, Tofghi *et al.* [7] who modelled the flow around different shaped disks using a 2D ISPH method and Aly and Asai [8] who looked at simulating flood disaster using ISPH. However, none of these works looked at problems involving many rigid bodies interacting with each other as well as the fluid. Using SPH to model flows that contain short fibres has been described in the literature. One of the first cases of this was presented by Kulasegaram and Karihaloo [9], which was further developed by Deeb *et al.* [10]. They used incompressible SPH to model the non-Newtonian fluid and rigid body fibres. This was also the focus of the work by Husek *et al.* [11]. Cleary *et al.* [12]–[15] used SPH to simulate a 3D die-casting process where the applications ranged from household products to automotive components. SPH modelling of composite manufacturing has also been applied to the injection molding process [16]–[18] and to 3D printing [19]. Whilst these applications share some similarities with this work in terms of the suspension of short fibres in a medium, the flows investigated were all much more viscous than the fluid used in this work.

Of particular interest in this work is the final orientation and alignment of the fibres, as this has a large influence on the overall mechanical properties of the final structure and leads to a component that can compete with traditional continuous fibre products. The fibre orientation has been studied by Skoptsov *et al.* [20] for the injection molding process and was also the focus of the investigation of Deeb *et al.* [21] for self-compacting concrete. There have also been several other studies of fibre orientation not using SPH such as that of Oumer *et al.* [22] and Khodadadi Yazdi *et al.* [23], but the most relevant for this work is perhaps the study by Hamalainen *et al.* [24] who investigated the fibre alignment of a paper-making process which has a very similar setup to the HiPerDiF method modelled in this work.

The remainder of this paper is organised as follows: section II describes the HiPerDiF process in more detail and section III outlines the SPH methodology used in this work. Section IV presents the results of this investigation whilst section V concludes the paper.

II. THE HiPERDiF METHOD

The HiPerDiF technology enables the manufacture of highly aligned discontinuous composite tapes. A schematic of the current HiPerDiF machine is shown in Fig. 1.

The first stage consists of a suspension tank in which the short fibres are dispersed. The mixture of the fluid and fibres is then transported through a network of pipes to the alignment head. This is achieved using a peristaltic pump. The fibre alignment head, shown in Fig. 2, is made up of a number of nozzles and an array of thinly-spaced parallel plates. The purpose of the alignment head is to spray the water/fibre mixture towards the plates. The mixture hits the plates and, due to the narrow spacing, the fibres are forced to align along

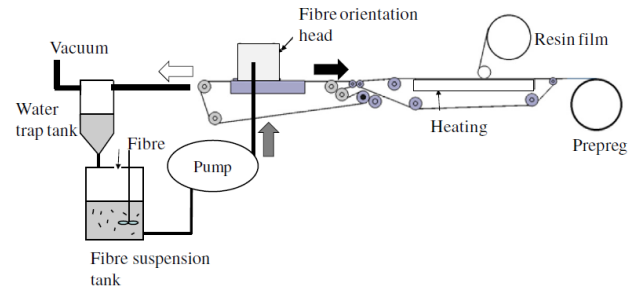


Fig. 1. HiPerDiF composite manufacturing process

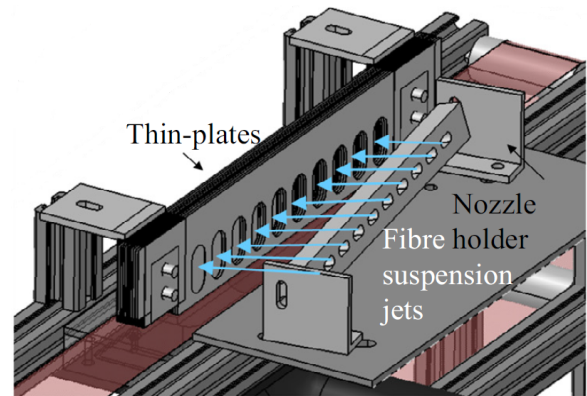


Fig. 2. HiPerDiF alignment head setup [5]

a mesh conveyer belt arranged at the base of the plates. It is important for the conveyer belt to be perforated in order for the water to be extracted, which is done with the aid of a suction pump, without affecting the alignment of the fibres. After the water is removed, the fibres are still slightly damp so they are carried on the belt to a drying station before being impregnated with the resin. The end product is the highly aligned discontinuous fibre composite tape.

The main focus of the current project is the upscaling of the HiPerDiF technology to enable a much higher production rate. This requires a higher throughput of material but the alignment level of the fibres must be at least maintained. The alignment mechanism is a fluid-structure interaction problem and before informing the next generation machine, the SPH method used to model the alignment head must be validated. This model can then be used to investigate the effects of changing different problem parameters such as nozzle angle, plate shape and belt speed on the final fibre alignment.

III. SPH METHOD

The numerical method used to simulate the HiPerDiF alignment mechanism is described below. Although the methodology used here is a standard WCSPH formulation, details are included for completeness.

A. Fluid

The weakly compressible form of the SPH equations are used such that the momentum equation is given by (1)

$$\begin{aligned} \frac{D\mathbf{u}_i}{Dt} = & - \sum_{j=1}^N m_j \left[\frac{p_j}{\rho_j^2} + \frac{p_i}{\rho_i^2} \right] \nabla W_{ij} \\ & + \sum_{j=1}^N m_j \nu \frac{\rho_i + \rho_j}{\rho_i \rho_j} \frac{\mathbf{x}_{ij} \cdot \nabla_i W_{ij}}{|\mathbf{x}_{ij}|^2 + 0.001h^2} \mathbf{u}_{ij} \\ & + \frac{1}{m_i} \mathbf{F}_i + \mathbf{g} \end{aligned} \quad (1)$$

where the second term on the right hand side of (1) is the viscosity term proposed by Morris *et al.* [25] and the third term is pairwise force surface tension described by Tartakovsky and Meakin [26]. Wendland's C2 kernel is used throughout this work. The continuity equation is evolved according to (2)

$$\frac{D\rho}{Dt} = - \sum_{j=1}^N m_j (\mathbf{u}_i - \mathbf{u}_j) \cdot \nabla_i W_{ij} \quad (2)$$

and Tait's equation is used as the equation of state to compute the pressures. The solid plate boundary conditions are modelled using dynamic boundary particles as originally proposed by Dalrymple and Rogers [27] and later developed by Crespo *et al.* [28], which means (2) is solved on the boundary particles, and the pressures are updated accordingly, but (1) is not. The equations are evolved using the Newmark-beta scheme as explained by Hall *et al.* [29].

B. Fibres

The fibres are also simulated using the SPH formulation but are treated as rigid bodies. Each fibre consists of a number of SPH particles, so that both momentum and continuity are solved for each fibre particle. The linear and angular velocities, V and Ω respectively, of each fibre can then be updated using (3) and (4)

$$M \frac{dV}{dt} = F \quad (3)$$

$$I \frac{d\Omega}{dt} = T \quad (4)$$

where M is the mass of the fibre, F is the total force on the fibre computed by summing the contribution from the particles that belong to it, I is the inertia matrix and T is the torque. The fibres are modelled as thin rods meaning that there is no rotation about length. The velocities computed using these equations can then be used to update the positions of all of the particles on a given fibre.

IV. RESULTS

This work aims to validate the SPH model used to simulate the HiPerDiF alignment head. This is done in two ways: firstly, the shape of the jet at different timesteps is compared and secondly, the fibre alignment produced using three different plate spacings is qualitatively compared. In this section the results of this validation work are shown before the model

is used to investigate the effect of the jet velocity on fibre alignment but first the experimental and computational setups are described.

1) *Experimental setup*: The experiments used a smaller prototype version of the HiPerDiF machine. The working principles are the same but the alignment head consists of two nozzles as shown in Fig. 3. The validation was carried out by comparing the effect of different plate spacings on the fibre alignment. Three different plate spacings were used: 0.3mm, 0.5mm and 1.0mm. All other settings remained constant and are listed in Table I.

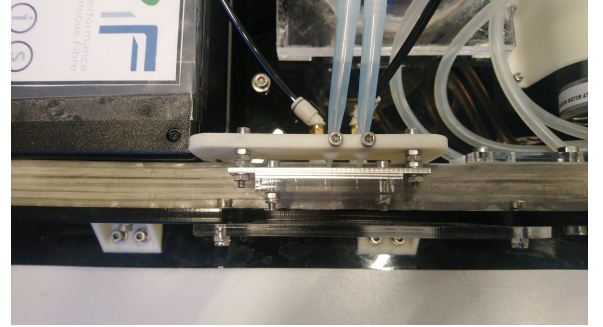


Fig. 3. Smaller prototype HiPerDiF alignment head

TABLE I
EXPERIMENTAL PARAMETERS

Parameter name	Value	Units
Nozzle angle θ	45.0	degrees
Nozzle angle ϕ	45.0	degrees
Nozzle diameter	1.35	mm
Flow rate	2.35	mL/s
Belt speed	14	mm/s
Fibre length	3.0	mm
Fibre density	1820	kg/m ³
Fibre volume concentration	0.0005	%

A. Computational setup

The computational setup was designed to closely match the experiments. Most parameters are straightforward to implement such as the nozzle angles, belt speed and fibre properties. The HiPerDiF technology uses a peristaltic pump to spray the fluid/fibre mixture through the nozzles. This causes a pulsing effect of the mixture. Using a high speed imaging camera a single on/off pulse was timed at 0.05 seconds, consisting of 0.025 seconds on and 0.025 seconds off. To replicate this effect in the simulation the velocity of particles added to the nozzle was set according to its temporal position in the pulse and the pulse was modelled by a sinusoidal function as shown in Fig. 4. The magnitude of the function was chosen so that the overall flow rate matched the value calculated in the experiments. Also, the fibre concentration was used to calculate the number of fibres assuming that the fibres are evenly dispersed in the water and evenly supplied to the nozzles. This resulted in four fibres per nozzle per pulse.

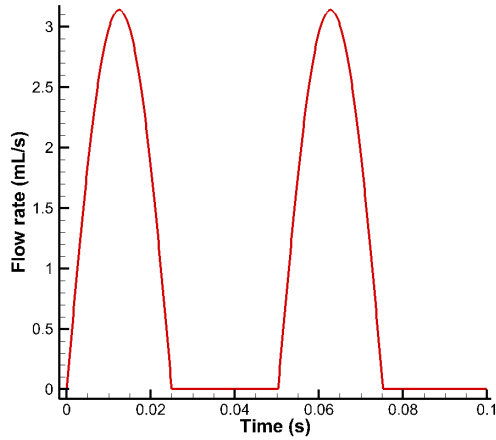


Fig. 4. Jet pulse function

For all three plate spacings, the particle smoothing length was kept constant. The resolution requirements are primarily driven by the plate spacing, due to the need to accurately resolve the gap. It is important to resolve the gap but not to over-resolve it as this unnecessarily increases the computational cost. Therefore, the smallest plate spacing was used to determine the smoothing length, which was set to 0.09mm, which is 1.5 times the initial particle spacing. All the simulation parameters are provided in Table II.

TABLE II
COMPUTATIONAL PARAMETERS

Parameter name	Value	Units
Initial particle spacing	0.06	mm
Surface tension coefficient	0.0728	N/m
Smoothing length	0.09	mm
Contact angle (plates)	71.0	degrees
Contact angle (fibres)	80.0	degrees
Timestep size	2×10^{-7}	seconds
FSI loop iterations	2	n/a

B. Validation results

The formation of the jet as it impinges the back plate was captured using a high speed camera. The camera was a Photron FASTCAM SA-Z and took images at 2000 frames per second. The images were taken from behind the plate. Fig. 5 shows the shape the jet forms on the plate at different instances of the pulsing action. Comparison of the experimental jet, Fig. 5(a), and the computational jet, Fig. 5(b), shows the simulations match the experimental reality reasonably well.

For each plate spacing, the preform produced was carefully transferred to a glass slide and imaged. The fibre alignment for the three different plate spacings is shown in Fig. 6. It is clear that the experimental alignment decreases as the plate spacing increases and this trend is captured by the SPH model. The use of a computational model also makes it easy to calculate

the level of fibre alignment for each case. In the first paper describing the HiPerDiF technology [1], the alignment was quantified by calculating the percentage of fibres with an orientation of $\pm 3^\circ$ therefore this is the metric also used in this work. The fibre alignment for the three different plate spacings is shown in Fig. 7. It is clear to see that there is an increase in the level of alignment as the plate spacing is decreased with the smallest plate spacing having 75% of fibres aligned within $\pm 3^\circ$. This gives an indication of the quality of the final composite tape as the alignment significantly affects mechanical properties.

C. Effect of jet velocity

Having validated the model, the effect of the jet velocity on the fibre alignment was investigated. For these simulations the pulsing effect of the jet was ignored, instead a continuous flow was modelled for four different velocities: 0.4m/s, 0.8m/s, 1.6m/s and 3.2m/s. These jet velocities were investigated for two different plate spacings: 0.3mm and 1.0mm. A continuous jet with velocity 0.8m/s displaces the same amount of fluid in 0.05 seconds as the pulsing jet simulated previously. The number of fibres introduced was constant with respect to time for all velocities, thus meaning that the faster jets had a lower fibre concentration than the slower ones. The fibre alignment for the four different jet velocities are shown in Fig. 8 and Fig. 9 for a plate spacing of 0.3mm and 1.0mm, respectively. It is clear to see that the level of alignment is largely unaffected by the jet velocity. For the smaller plate spacing there is very little difference between any of the simulations. For the largest plate spacing, the effect of increasing jet velocity is to stretch the placement of fibres out in the belt direction, which results in both a thinner tape and one that would contain more voids, thus having lower quality.

V. CONCLUSION

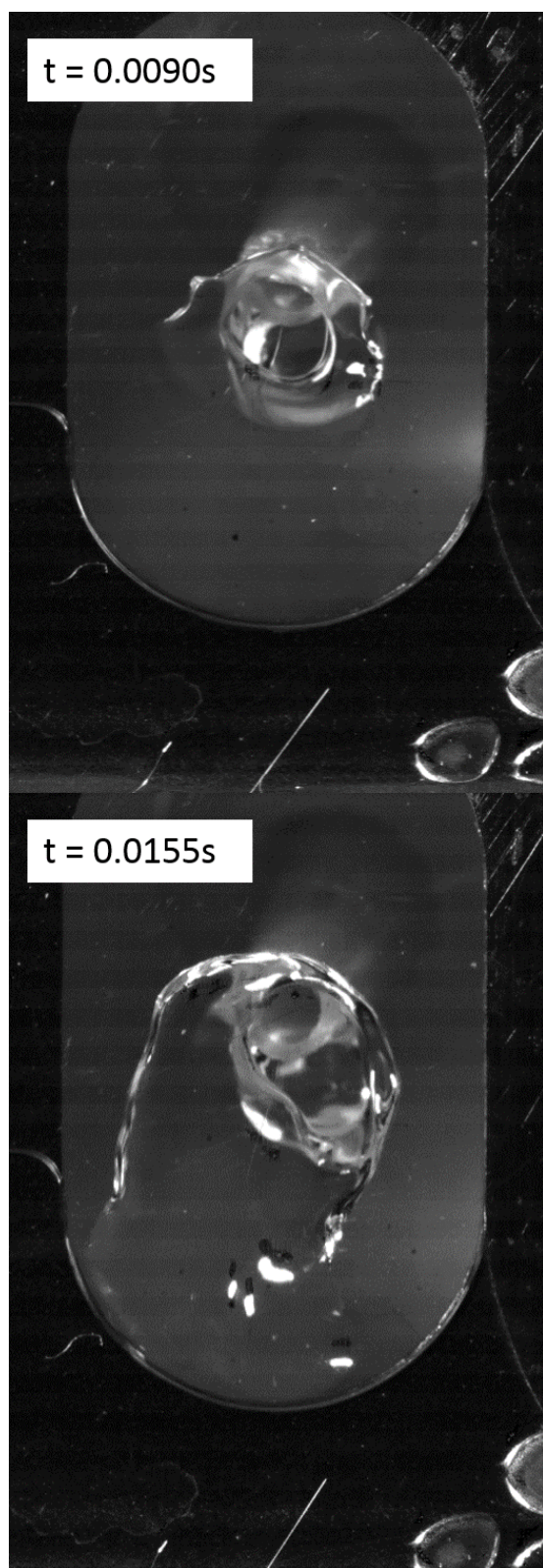
A numerical fluid model for deposition of suspended fibres has been presented based on smoothed particle hydrodynamics. The model includes all fluid-fibre effects, as well as the influence of the peristaltic pump, pressure-driven fluid drainage and moving belt. Accuracy has been assessed against experimental results by varying the plate spacing of the tape laying machine, and the numerical model has been shown to correctly reproduce the variations in fibre alignment observed. Future work will focus on higher fidelity modelling of the system as the HiPerDif machine design progresses.

ACKNOWLEDGMENT

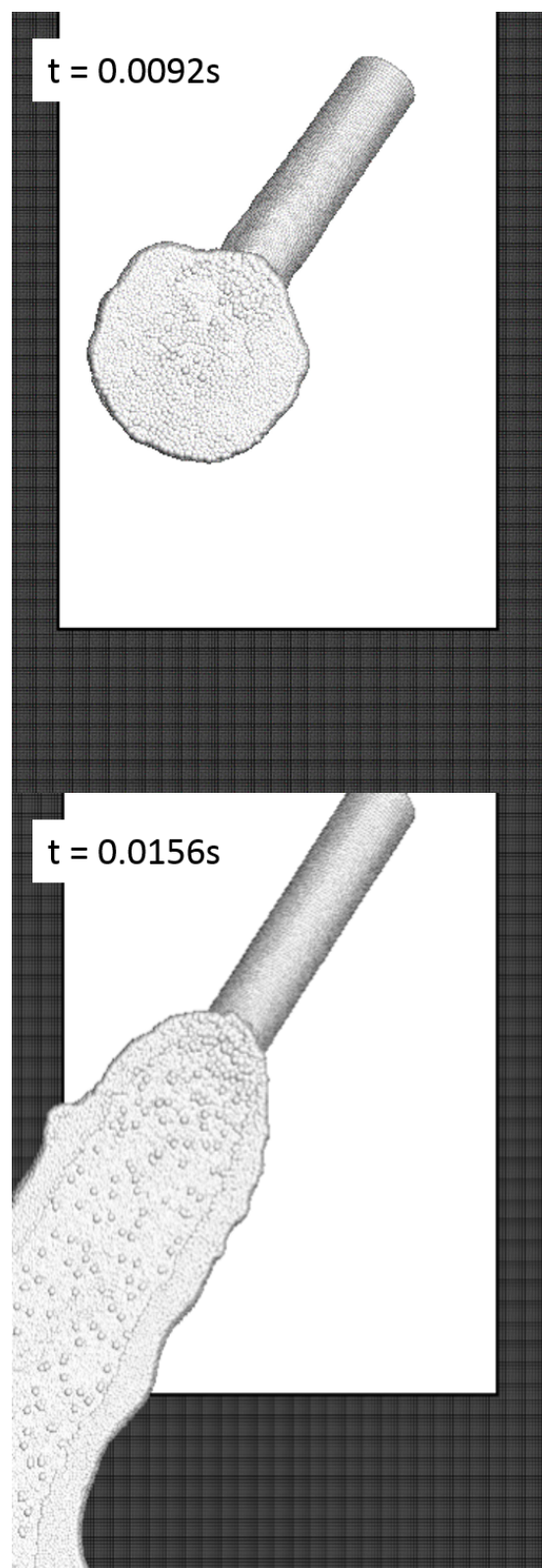
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REFERENCES

- [1] H. Yu, K. Potter, and M. Wisnom, "A novel manufacturing method for aligned discontinuous fibre composites (high performance-discontinuous fibre method)," *Composites: Part A*, vol. 65, pp. 175–185, 2014.



(a) Experiment



(b) Computational

Fig. 5. Simulation results

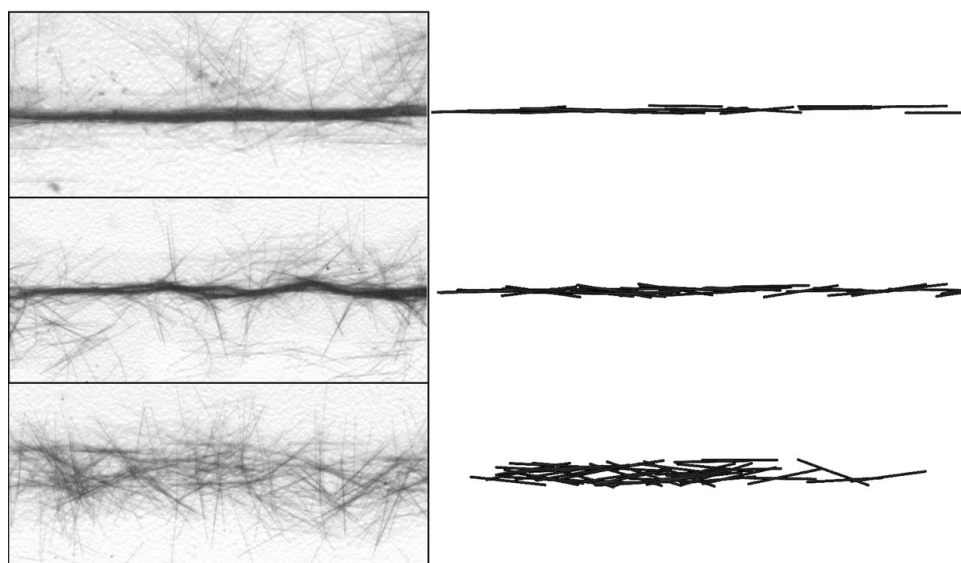


Fig. 6. Fibre alignment from experiments (left) and simulations (right) for plate spacings of 0.3mm (top), 0.5mm (middle) and 1mm (bottom)

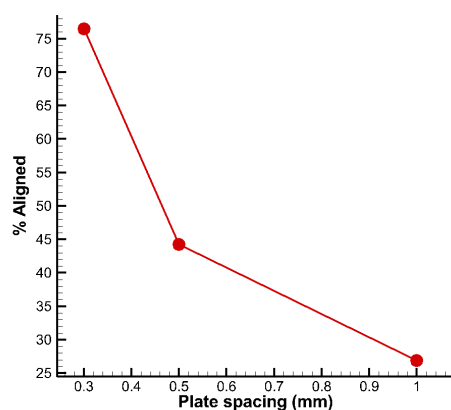


Fig. 7. Effect of plate spacing on fibre alignment



Fig. 8. Fibre alignment for plate spacings of 0.3mm for jet velocities of 0.4m/s, 0.8m/s, 1.6m/s, 3.2m/s (top to bottom)



Fig. 9. Fibre alignment for plate spacings of 1.0mm for jet velocities of 0.4m/s, 0.8m/s, 1.6m/s, 3.2m/s (top to bottom)

- [2] S. Halliwell, "End-of-life options for composite waste: recycle, reuse or disposal? national composites network best practice guide," Chesterfield, UK, 2006.
- [3] M. Longana, N. Ong, H. Yu, and K. Potter, "Multiple closed loop recycling of carbon fibre composites with the hiperdif (high performance discontinuous fibre) method," *Composite Structures*, vol. 153, pp. 271–

- 277, 2016.
- [4] M. Such, C. Ward, and K. Potter, "Aligned discontinuous fibre composites: A short history," *Journal of Multifunctional Composites*, vol. 3, 2014.
- [5] H. Yu, M. Longana, M. Jalalvand, M. Wisnom, and K. Potter, "Hierarchical pseudo-ductile hybrid composites combining continuous and highly-aligned discontinuous fibres," *Composites: Part A*, vol. 105, pp. 40–56, 2018.
- [6] M. Hashemi, R. Fatehi, and M. Manzari, "A modified sph method for simulating motion of rigid bodies in newtonian fluid flows," *International Journal of Non-Linear Mechanics*, vol. 47, pp. 626–638, 2012.
- [7] T. Tofighi, M. Ozbulut, A. Rahmat, J. Feng, and M. Yildiz, "An incompressible smoothed particle hydrodynamics method for the motion of rigid bodies in fluids," *Journal of Computational Physics*, vol. 297, pp. 207–220, 2015.
- [8] A. Aly and M. Asai, "Large scale simulation of fluid-structure interaction using an incompressible smoothed particle hydrodynamics," in *11th World Congress on Computational Mechanics*, E. Oate, J. Oliver, and A. Huerta, Eds., vol. 11. International Association for Computational Mechanics, 2014.
- [9] S. Kulasegaram, B. Karihaloo, and A. Ghanbari, "Modelling the flow of self-compacting concrete," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 35, pp. 713–723, 2011.
- [10] R. Deeb, S. Kulasegaram, and B. Karihaloo, "3d modelling of the flow of self-compacting concrete with or without steel fibres. part i: slump

- flow test," *Computational Particle Mechanics*, vol. 1, pp. 373–389, 2014.
- [11] M. Husek, J. Kala, P. Kral, and F. Hokes, "Steel fibre reinforced concrete simulation with the sph method," in *IOP Conf. Series: Materials Science and Engineering*, vol. 245. IOP Publishing Ltd, 2017.
- [12] P. Cleary, J. Ha, M. Prakash, and T. Nguyen, "3d sph flow predictions and validation for high pressure die casting of automotive components," *Applied Mathematical Modelling*, vol. 30, pp. 1406–1427, 2006.
- [13] P. Cleary and J. Ha, "Three-dimensional smoothed particle hydrodynamics simulation of high pressure die casting of light metal components," *Journal of Light Metals*, vol. 2, pp. 169–183, 2009.
- [14] P. Cleary, J. Ha, M. Prakash, and T. Nguyen, "Short shots and industrial case studies: Understanding fluid flow and solidification in high pressure die casting," *Applied Mathematical Modelling*, vol. 34, pp. 2018–2033, 2010.
- [15] P. Cleary, G. Savage, J. Ha, and M. Prakash, "Flow analysis and validation of numerical modelling for a thin walled high pressure die casting using sph," *Computational Particle Mechanics*, vol. 1, pp. 229–243, 2014.
- [16] D. Su, R. Ma, and L. Zhu, "Numerical study of liquid composite molding using a smoothed particle hydrodynamics method," *Special Topics & Reviews in Porous Media - An International Journal*, vol. 2, pp. 205–216, 2011.
- [17] X. Xu, J. Ouyang, B. Yang, and Z. Liu, "Sph simulations of three-dimensional non-newtonian free surface flows," *Computer Methods in Applied Mechanical Engineering*, vol. 256, pp. 101–116, 2013.
- [18] L. He, G. Lu, D. Chen, W. Li, and C. Lu, "Three-dimensional smoothed particle hydrodynamics simulation for injection molding of short fiber-reinforced polymer composites," *Modelling and Simulation in Materials Science and Engineering*, vol. 25, no. 055007, 2017.
- [19] D. Yang, K. Wu, L. Wan, and Y. Sheng, "A particle element approach for modelling the 3d printing process of fibre reinforced polymer composites," *Journal of Manufacturing and Materials Processing*, vol. 1, no. 10, 2017.
- [20] K. Skoptsov, V. Sheshenin, V. Galatenko, A. Malakho, N. Shornikova, V. Avdeev, and V. Sadovnichy, "Particle simulation for predicting effective properties of short fiber reinforced composites," *International Journal of Applied Mechanics*, vol. 8, no. 1650016, 2016.
- [21] R. Deeb, S. Kulasegaram, and B. Karihaloo, "3d modelling of the flow of self-compacting concrete with or without steel fibres. part ii: L-box test and the assessment of fibre reorientation during the flow," *Computational Particle Mechanics*, vol. 1, pp. 391–408, 2014.
- [22] A. Oumer, N. Hamidi, and I. Mat Sahat, "Numerical prediction of flow induced fibers orientation in injection molded polymer composites," in *IOP Conf. Series: Materials Science and Engineering*, vol. 100. IOP Publishing Ltd, 2015.
- [23] M. Khodadadi Yazdi, A. Ramazani S.A., A. Kamyabi, and H. Hosseini Amoli, "Simulation of flow of short fiber suspensions through a planar contraction," *Transactions C: Chemistry and Chemical Engineering*, vol. 19, pp. 579–584, 2012.
- [24] J. Hamalainen, T. Hamalainen, T. Leppanen, H. Niskanen, and J. Sorvari, "Mathematics in paper - from fiber suspension fluid dynamic to solid state paper mechanics," *Journal of Mathematics in Industry*, vol. 4, no. 14, 2014.
- [25] J. Morris, P. Fox, and Y. Zhu, "Modeling low reynolds number incompressible flow using sph," *Journal of Computational Physics*, vol. 136, pp. 214–226, 1997.
- [26] A. Tartakovsky and P. Meakin, "Modeling of surface tension and contact angles with smoothed particle hydrodynamics," *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics*, vol. 72, no. 026301, 2005.
- [27] R. Dalrymple and B. Rogers, "Numerical modeling of water waves with the sph method," *Coastal Engineering*, vol. 53, pp. 141–147, 2006.
- [28] A. Crespo, M. Gomez-Gestaira, and R. Dalrymple, "Boundary conditions generated by dynamic particles in sph methods," *Computers, Materials & Continua*, vol. 5, no. 3, pp. 173–184, 2007.
- [29] J. Hall, T. Rendall, C. Allen, and H. Peel, "A multi-physics computational model of fuel sloshing effects on aeroelastic behaviour," *Journal of Fluids and Structures*, vol. 56, pp. 11–32, 2015.